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Investigating Immersive Virtual Reality as an Educational Tool for Quantum Computing

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ABSTRACT

Quantum computing (QC) is an intrinsically complex yet exciting discipline with increasing practical relevance. A deep understanding of QC requires the integration of knowledge across numerous technical fields, such as physics, computing and mathematics. This work aims to investigate how immersive Virtual Reality (VR) compares to a desktop environment ('web-applet') as an educational tool to help teach individuals QC fundamentals. We developed two interactive learning tutorials, one utilising the 'Bloch sphere' visualisation to represent a single-qubit system, and the other exploring multi-qubit systems through the lens of 'quantum entanglement'. We evaluate the effectiveness of each medium to teach QC fundamentals in a user study with 24 participants. We find that the Bloch sphere visualisation was well-suited to VR over a desktop environment. Our results also indicate that mathematics literacy is an important factor in facilitating greater learning with this effect being notably more pronounced when using VR. However, VR did not significantly improve learning in a multi-qubit context. Our work provides valuable insights which contribute to the emerging field of *Quantum HCI (QHCI)* and VR for education.

CCS CONCEPTS

• **Human-centered computing** → **Virtual reality**.

KEYWORDS

Quantum Computing, Virtual Reality, Education, Learning

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1 INTRODUCTION

Quantum computing (QC) is an exciting yet conceptually challenging discipline. QC is intrinsically complex and cross-disciplinary, requiring mastery of concepts from physics, computer science and mathematics. Additionally, quantum computers are getting ever-closer to becoming a physical reality rather than a mere academic exercise [45]. However, the cross-disciplinary nature of QC presents domain-specific pedagogical challenges. For example, the average computer science graduate is likely to be well-versed in information theory principles, but not quantum mechanics (QM). For most students, QM is an abstract and conceptually challenging field which typically involves difficult mathematical formalisms [17].

QM is incompatible with a conception of reality modeled on classical physics [18]. In general, *classical* mechanics accurately models the macroscopic world we have evolved to live in. If an apple falls off a tree it will, predictably, accelerate towards the ground along a single vertical path. However, QM presents a radically different world view, which suggests that such deterministic behaviour is an illusion of scale. Instead, a *particle* moving from one point to another could take many different paths 'simultaneously', what known as a *superposition* state. Even more counter-intuitive, if we were to try to *measure* the path this particle takes, this superposition would 'collapse' randomly as though only one path was taken. The notion that observing a system can change its state is foreign, and simply does not reflect any phenomena we experience at our macroscopic scale. Fortunately, to develop an understanding of QC, one does not require *deep* knowledge of QM [38]. It is possible to comprehend QC with a basic understanding of QM concepts such as superposition, entanglement and quantum measurement.

Within the emerging realm of *Quantum-Human Computer Interaction (QHCI)*, exploring different means of teaching these principles is crucial to help individuals adapt to a world where QC will become increasingly relevant [4]. Textbooks already explore QC in depth with different audiences in mind. For example, Nielsen and Chuang [32] focus on a technical and comprehensive review of the field (commonly known as the 'bible' of QC), whereas Rieffel and Polak [38] focus on teaching QC to individuals across a larger variety of educational backgrounds. In recent years, interactive software has been used as part of higher-education curricula on QC in order to help individuals across a wide array of backgrounds grapple with its complexities [28].

In a similar vein, our work aims to investigate how interactive technology can help individuals with differing educational backgrounds better understand QC. In particular, our focus is on using immersive Virtual Reality (VR) to conceptualise principles of *quantum information theory* in the context of QC more broadly. Researchers have extensively investigated immersive VR as a medium to facilitate and enhance learning in higher-education [36]. A key strength of immersive VR is that it allows users to engage with abstract ideas which they otherwise could not in the real world [15]. On this basis, VR is ideally suited to convey ideas heavily reliant upon QM phenomena, such as those within the realm of QC. While we may not be able to personally *experience* these phenomena in our day-to-day lives, we are able to come close within the confines of a virtual world.

Our work explores how VR *compares* to a conventional desktop environment (i.e. ‘web-applet’) as a learning medium. We developed two cross-platform interactive learning tutorials, designed to teach concepts relevant to ‘single-qubit’ and ‘multi-qubit’ systems respectively. We conducted a user study utilising these tutorials to determine the effectiveness of each medium in terms of learning gains. Our results indicate that a single-qubit visualisation known as ‘The Bloch sphere’ is particularly well suited to a VR environment. This effect was more pronounced for participants who were also literate in mathematics. In a multi-qubit context, we did not find statistically significant differences in learning with respect to the medium. Our work contributes to a growing body of research on leveraging VR as powerful tool in different educational scenarios. To our knowledge, this is the first time VR has been studied in a scenario focusing on QC education.

2 RELATED WORK

There are a few pillars of related research that provide a rationale for our work. We firstly summarise QC as a theoretical field in order to provide context with respect to the key QM concepts that underpin it – *superposition*, *entanglement* and *measurement*. We also outline an existing visualisation for particular quantum states known as the ‘Bloch sphere’. We then review the emerging field of Human-Quantum Computer Interaction (QHCI), and how physics education research has examined related concepts using interactive computer simulations. Finally, we review previous work which has investigated the use of VR in educational settings.

2.1 Quantum Computing

Quantum computers extend the notion of a ‘classical bit’ to that of a ‘quantum bit’, usually known as a *qubit*. A *bit* can take one of two values—‘0’ or ‘1’. A *qubit* may similarly encode the states ‘0’ or ‘1’ like a bit, but it may also encode a *superposition* of these two states [38]. A superposition is a (non-trivial) linear combination of ‘basis’ states where the coefficients are complex numbers [38]. The internal state of a quantum computer can be represented by a vector of complex numbers. An important constraint in a quantum computer is that the state vector must always be a *unit* vector. It follows that the general state of a single-qubit quantum computer can be captured by the equation:

$$|\psi\rangle = \alpha |0\rangle + \beta |1\rangle \quad (1)$$

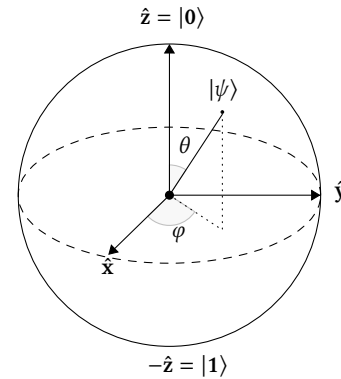


Figure 1: Illustration of the ‘Bloch sphere’ in some arbitrary state $|\psi\rangle$.¹

Here α and β are complex numbers, and $|\alpha|^2 + |\beta|^2 = 1$ (since the state vector must be a unit vector). Note that a special notation known as ‘bra-ket’ notation is used to describe quantum states as seen above. For example, $|\psi\rangle$, $|0\rangle$ and $|1\rangle$ are known as ‘kets’, which are members of a linear space. A single-qubit system can be represented using a three-dimensional visualisation known as the ‘Bloch sphere’ [12]. In this representation, the state of the system is a unique point on the surface of the sphere (Figure 1). The north and south poles of the sphere represent the $|0\rangle$ and $|1\rangle$ states respectively, while points in-between represent superpositions with respect to these states. An arbitrary point on the sphere is parameterised by two angles, θ and φ – see [12] for a full derivation.

Quantum *computation* is only possible when we increase the number of qubits in a system beyond just one. We are particularly interested in *entangled* qubits, which do not exist in isolation from one another. More formally, when the state of one qubit cannot be described independently of another, we say that they are entangled. It is possible for entanglement to vary in its ‘degree’. For example, two qubits might be *maximally* entangled, or *partially* entangled. Entanglement can affect inferences made about a quantum system when it is *measured*. For example, measuring the state of a qubit which is entangled with another, can affect the measurement outcome of that qubit.

Entanglement is critical to the power of quantum algorithms. A strong understanding of entanglement is fundamental to understanding what gives a quantum computer an edge over a classical computer. Once a system is entangled, the Bloch sphere visualisation breaks down, because the state space cannot be condensed into three-dimensions in the same form. For a more comprehensive introduction to the concepts discussed here, see Rieffel and Polak [38] or Kaye et al. [21].

2.2 Quantum HCI

Given its increasing practical relevance, QC has recently become of interest within the domain of Human-Computer Interaction (HCI). Ashktorab et al. [4] recently coined the term *Quantum HCI* (QHCI), which encompasses the study of the interaction between people

¹Latex credit: <https://tex.stackexchange.com/questions/345420/how-to-draw-a-bloch-sphere>

and quantum computing systems, as opposed to traditional systems. The authors note that developing educational materials is a key area of research interest. Several researchers have already explored *innovative* approaches to engage in QC education, given the highly technical nature of the field. One such recent example is a board game called *Entanglion* whereby players navigate two spaceships through a virtual universe retrieving quantum computer components [50]. Each space ship represents a qubit, and planets in the universe represent the various quantum states. The game is a simulation of a two qubit system, introducing players to fundamental QC principles. An evaluation among experts and high-school students revealed that it was an enjoyable as well as educational experience.

Other innovative approaches to QC education have also been developed for use in higher education. Hollenberg et al. [28] developed a quantum computer simulator that runs in a web browser called the Quantum User Interface (QUI). The QUI is currently used in both undergraduate and postgraduate subjects that introduce students from non-physics backgrounds to QC. During ‘practical’ lab classes, students are instructed to perform experiments using the QUI. Students are able to program quantum algorithms on the simulated quantum computer system, as well as inspect and manipulate the internal state of the system across time.

Similarly, previous work has explored how interactive animations and simulations can enhance student understanding of QM and quantum information theory. Researchers have developed Quantum Interactive Learning Tutorials (QuILTs) [43] as well as interactive apps as part of the Quantum Mechanics Visualisation Project (QuVis) [22]. Topics explored include entanglement [25], superposition [23, 24], quantum measurement [54], and quantum key distribution [7, 26].

Our work contributes to this research agenda by shedding light on how immersive Virtual Reality (VR) compares to a desktop environment as an educational tool to assist students with QC fundamentals.

2.3 VR for Education

VR enables students to interact with virtual environments that not only model the real world, but also model abstract scenarios that may be difficult or impossible to replicate in the real world [15]. The student is the main protagonist in the virtual world, engaging with entities within it from a first-person perspective. Ultimately, this facilitates a ‘constructivist approach’ to learning [31]. *Constructivism* involves the student playing an active role in learning, whereby they construct their own understanding through their experiences [16].

While QC education is a novel application of VR, a significant body of research has explored how VR can be used as an educational tool generally. Obvious applications include simulating learning scenarios which could otherwise put lives at risk, such as in medical and surgical contexts [35, 39]. Some medical training scenarios are also expensive due to the use of specialised equipment, making VR a cost-effective alternative [5]. Similarly, VR is helpful in safety training contexts. One such example is in mining, which is regarded as a high-risk industry requiring adherence to rigorous safety protocols [53].

VR has also been shown to be a particularly useful tool in engineering education [1, 2, 30, 40, 48]. Alhalabi [2] investigated how different types of VR systems (a room-scale virtual environment, and a three and a six degrees of freedom HMD) could be used to enhance student understanding of engineering concepts, compared with a traditional non-VR learning system. They found statistically significant improvement in learning in all the VR conditions compared with the no-VR condition, as well as evidence for improved performance in the HMD conditions over the CCS condition. Alhalabi [2] proposed that this might be due to the greater levels of immersion offered by HMDs. Similarly, VR has been successfully leveraged for geometry education. Kaufmann et al. [20] developed a three-dimensional geometric construction tool called ‘Construct3D’. The tool allows users to create and select basic primitives in a VR environment. In a subsequent iteration of the system, users rated it particularly highly in terms of “suitability for learning” [19]. Similar work has explored the use of a Samsung Gear HMD in facilitating the manipulation and measurement of 3D shapes in an immersive VR context [27].

A closely related area where VR may excel as an educational tool is in science teaching. Tsihouridis et al. [46] argue that ‘virtual laboratories’ facilitated by VR technologies offer a more engaging, creative, and importantly, *safe* space to conduct scientific experiments. Scientific thinking may be enhanced via a greater willingness to interact with an environment and perform experiments without fear of mistake-induced repercussions. Indeed, some scientific experimentation is genuinely risky or expensive to conduct in the real world, and VR allows less experienced individuals to conduct experiments that they otherwise couldn’t, thus accelerating learning.

Pirker et al. [33] describe the development and evaluation of a virtual physics laboratory called ‘Maroon’. The laboratory is designed in a general purpose way such that it can be easily deployed in ‘traditional’ contexts (e.g. mobile/web) as well as more cutting edge contexts (e.g. immersive VR HMDs). In this particular study, the authors deployed two particular variants of Maroon using both a room-scale fully immersive VR experience based on the HTC Vive, and a mobile VR equivalent based on the Samsung Gear VR system. Although the content was identical, the manner of interacting naturally depended on the VR technology used. By performing a qualitative evaluation with several students, the authors found that students thought the VR experience was not only particularly motivating, but a powerful way to visualise and rotate 3D objects. Their research provides evidence that physics environments can be captured effectively in a VR context.

Most relevant to our work, Dorland et al. [8] developed a VR game which introduces users to the world of quantum mechanics, and how it differs from the ‘classical’ world. A preliminary evaluation revealed that players of the game were more capable of identifying differences between quantum and classical systems compared with non-players. Our work also explores how QM concepts can be conveyed in a VR environment, but largely through the lens of QC. We also compare a VR environment to a conventional desktop environment in order to determine if VR itself confers specific pedagogical advantages. More broadly, we contribute to a growing body of research exploring how VR can be utilised as an educational tool in novel contexts.

3 METHOD

An important goal of this research is to investigate if immersive VR confers added educational value over a ‘conventional’ desktop-based equivalent (i.e. an interactive web applet) for learning QC concepts. In addition, we are also interested on whether there is an interaction effect between educational background and the learning medium in terms of learning outcomes. For example, it could be the case that VR can impart knowledge to ‘lay people’ to a greater extent than a conventional medium due to the higher levels of immersion and presence. Given the reliance on complex numbers in the field, mathematical literacy is an important measure to consider.

There is also a dichotomy between single-qubit and multi-qubit systems, since the concept of *entanglement* only applies in a multi-qubit context, and an entangled state requires more than three ‘dimensions’ to describe. Therefore, we also investigate whether VR can be useful both in single-qubit and/or multi-qubit contexts. To summarise, our work explores these research questions:

- (1) How does VR compare to a desktop environment in terms of conveying knowledge related to single-qubit systems?
- (2) How does VR compare to a desktop environment in terms of conveying knowledge related to multi-qubit systems?
- (3) What role does mathematical literacy, in particular knowledge of complex numbers, play in terms of facilitating learning in such contexts?

3.1 Learning tutorials

We developed two interactive learning tutorials in order to address the research questions as part of a subsequent user study. Each tutorial was designed to address concepts relevant to single-qubit and multi-qubit systems, in line with research questions 1 and 2. The tutorials were designed to be undertaken in sequence, as well as operate in a cross-platform manner. There were two target platforms; 1) a VR HMD environment (‘VR-based’) and 2) a desktop environment (‘desktop-based’). We used Unity to develop the tutorials using the ‘Android’ (VR) and WebGL build targets for the VR-based and desktop-based environments respectively.

The desktop-based tutorials were identical to the VR tutorials, except that they operated in a computer web browser. The only differences were that a mouse and keyboard was used for interaction (as opposed to VR hands and natural movement), and of course, there was no immersive stereoscopic vision, just a standard desktop display. Standard first-person controls (W-S-A-D keys to move, and mouse to look) were used for navigation in the desktop-based environment.

3.1.1 Tutorial A: ‘The Bloch sphere’. Tutorial A was designed to introduce users to single-qubit *superpositions*, primarily via the ‘Bloch sphere’ visualisation. The tutorial involves introducing users to an abstract ‘visualisation’ of a qubit, and how the visualisation differs as its state is changed (Figure 2). In this visualisation, a qubit is displayed as a glowing ‘orb’, noting that the user is explicitly told that this is purely a visualisation and that in reality we cannot ‘see’ a qubit like this. The orb’s colour is a linear combination of ‘blue’ and ‘red’ reflecting the underlying probabilities of it collapsing to the state ‘0’ or ‘1’ respectively. In addition to the visualisation, the user is provided with the respective state equation so they can develop a

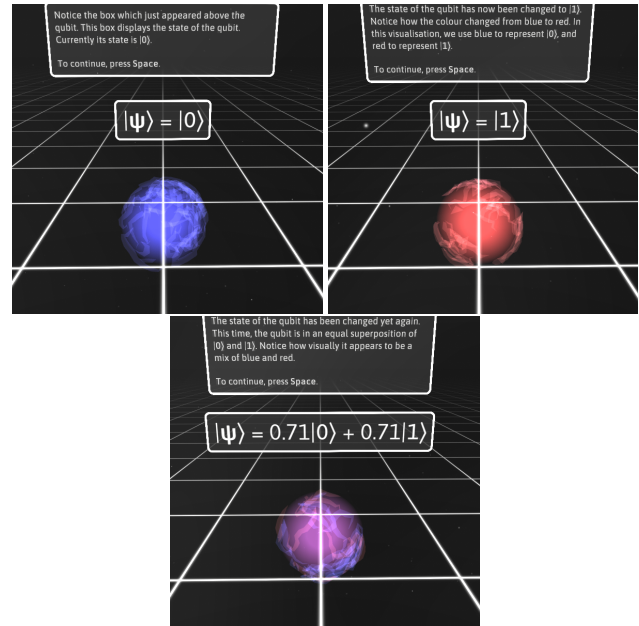


Figure 2: Visualisations of a qubit in various states. Blue and red hues are used to represent the states $|0\rangle$ and $|1\rangle$ respectively, and mixes of the two represent a superposition state (right).

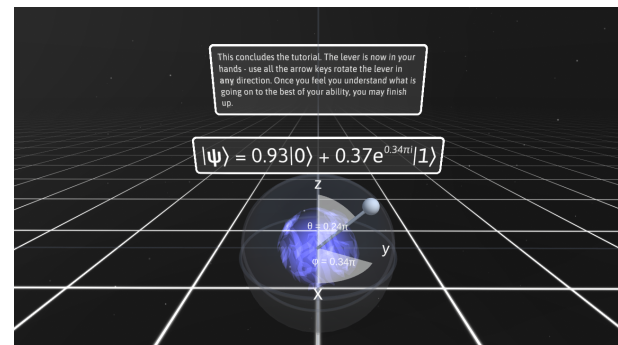


Figure 3: End-state of the Bloch sphere tutorial. The user has rotated the state lever to an arbitrary position on the surface of the sphere.

conceptual association between the relevant mathematical notation and the visualisation.

Following on from this, the user is introduced to the Bloch sphere visualisation. The Bloch sphere is superimposed over the qubit’s visualisation so that eventual changes in state on the Bloch sphere are easily seen reflected in the visualisation. The state ‘vector’ is depicted as a *lever* which sits on the surface of the sphere. Users are able to rotate the lever around the different axes of the sphere to watch how the state equation changes, but the specific interaction technique for accomplishing this depended on the platform of the system. In VR, users grabbed the lever to rotate it using virtual hands. In the desktop-based deployment, users used the arrow keys

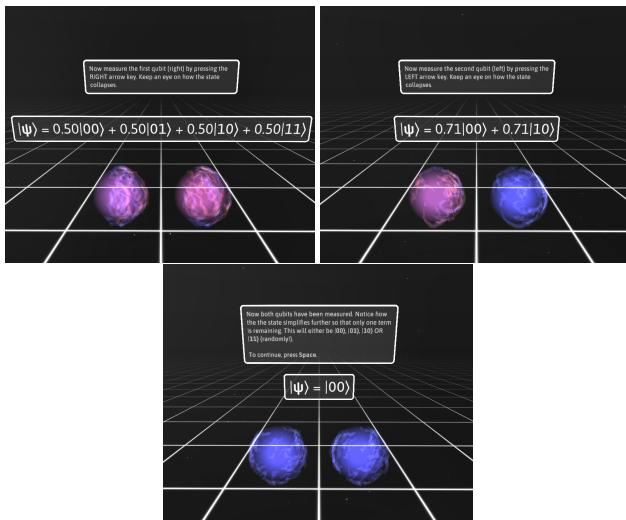


Figure 4: Measuring two unentangled qubits by first measuring the right qubit, and then the left qubit.

on their keyboard to rotate it (e.g. *yaw* and *pitch*). The user is shown how rotations around each axis of the Bloch sphere in turn affects the state of the qubit. In this stage, the lever is constrained to the movement of a single axis at a time (z , x , y), in order to illustrate the isolated effect of the two parameters (θ and ϕ). Upon the conclusion of the guided tutorial, the user is left to experiment and consolidate their knowledge in a free-form manner. In this stage, there are no more constraints applied to the lever, which can be rotated in any direction and the change in state observed (see Figure 3).

3.1.2 Tutorial B: ‘Entanglement’. We designed Tutorial B to introduce users to multi-qubit systems through the lens of quantum *entanglement*. Tutorial B used the same visualisation as Tutorial A for the qubits themselves, but did not include reference to the Bloch sphere as it does not generalise to multi-qubit states. The goal was to employ a *visuo-haptic* approach to learning [13]. In Tutorial B users can perform ‘quantum measurements’ by physically touching the qubits. The Oculus Touch controllers vibrate upon measurement, providing a simple form of tactile feedback. At the same time, the measured qubit visually pulsates while the measurement is performed, with the goal of increasing immersion via these two senses. In contrast, for desktop-based deployments, measurements can be performed simply by pressing a keyboard key, providing only visual feedback.

Tutorial B begins by introducing users to quantum measurement. This serves as a conceptual backbone for later understanding entanglement in terms of ‘correlated’ measurements. This is broken up into three phases, whereby repeated measurements are performed in order to consolidate the idea that the measurement is random. The first phase involves just a single-qubit system (following on from Tutorial A). The second phase involves a two-qubit system *without* entanglement present (Figure 4). Finally, the third phase involves a two-qubit system *with* (maximal) entanglement present (Figure 5).

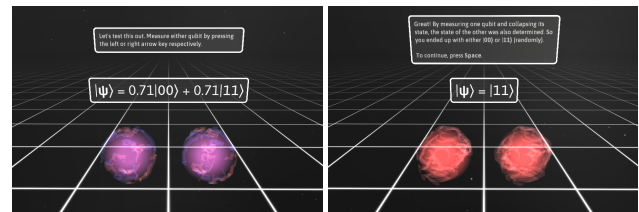


Figure 5: Measuring two maximally entangled qubits. In this instance, measurement of one qubit determines the measurement outcome of the other qubit.

It is important to note that a risk with describing entanglement in terms of measurement of a maximally entangled state is that it can lead to problematic misconceptions. Indeed, it is not uncommon for students to believe that, in general, knowing the measurement outcome of one qubit means we know for *certain* what the other will be [25]. A deeper understanding of the concept requires acknowledging that entanglement is a property of the *state* rather than the measurement outcomes of the qubits. In simple terms, when two qubits’ states cannot be described independently of each other, they are entangled. There are cases where measurement outcomes are more weakly correlated, or not even correlated at all.

To help address this concern, the final sequence of the tutorial aims to develop a deeper understanding of entanglement and its subtleties. The user is still given further examples of entangled states which exhibit ‘opposing’ or *partial* entanglement. Additionally, further context is provided regarding the idea that correlated measurements are only a possible *consequence* of entanglement, not the defining characteristic. It is also illustrated through a brief experiment how entanglement is a ‘spooky’ phenomenon which theoretically operates across vast distances. The qubits are reverted to a Bell state, and one of the qubits is sent far away (outside of the view). ‘Alice’ receives the qubit in this far away place. The user is then asked to measure their qubit and guess what state Alice would measure. The qubit is returned to its former location (in the view) so the user can verify that the state collapsed as predicted. Here, the tutorial concludes and enters a similar ‘end-state’ to Tutorial A. The user is given unlimited opportunity to continuously generate and measure new two-qubit states—some entangled, some not.

3.2 User study

3.2.1 Participants and Recruitment. We recruited 24 participants (5 women, 18 men, 1 not disclosed) with a mean age of 27.7 (SD = 10.9) for the experiment. Recruitment involved advertisements listed on online university notice boards, as well as online enthusiast forums for the Oculus Quest HMD. A key advantage of the Quest HMD is that it is totally detached from a computer and it offers both head and hands tracking with six degrees of freedom. This allows for easy exploration of a virtual space without any concern over a user getting tangled in wires disturbing the learning process. A pre-experiment questionnaire was used to record demographic information and educational background of interested candidates. We did not include candidates that reported having an in-depth understanding of Quantum Mechanics. Suitable candidates were contacted by email with instructions on how to register.

Most participants partook in the study remotely using the video-conferencing software *Zoom* due to COVID-19 restrictions. Steed et al. [44] note that the use of non-uniform apparatus is a potential threat to validity in remote VR studies. We mitigated this risk by only recruiting VR participants who owned the designated target hardware (Oculus Quest). Unlike many other HMDs, the Oculus Quest is not reliant upon PC hardware, which can vary significantly in terms of VR rendering throughput.

Furthermore, participants were asked to run the tutorial app in advance of the experiment and provide us with a randomly generated ‘activation key’ (displayed within the virtual world on a panel). This ensured the app operated correctly in their environment. This system also allowed us to activate the tutorials for a respective participant during the experiment itself so they had no prior exposure to them. The experimental design was approved by our University’s human ethics advisory committee.

3.2.2 Knowledge Tests. We developed knowledge tests in order to quantify the learning outcomes associated with tutorials A and B. There were two tests, ‘knowledge test A’ and ‘knowledge test B’, each aimed at measuring knowledge relevant to the respective tutorial. The tests were designed to be administered both before and after exposure to the learning tutorials. Both tests were comprised exclusively of multiple choice questions, with four candidate answers per question. Each test was five questions long, and was designed to take at most five minutes. This allowed two tests to be administered twice during a one hour experiment, along with the learning itself and other relevant questionnaires. In order to mitigate issues related to accidentally guessing correct answers, each question was paired with a measure of self-confidence on a Likert scale between 1 and 7. Participants were asked to rate their answer between ‘1’ if they guessed it completely, and ‘7’ if they were certain it was correct.

3.2.3 Procedure. All 24 participants completed tutorial A and tutorial B in that order. Given that the content in tutorial B pedagogically depends on the content in tutorial A, tutorial B was always completed last. The tutorials themselves were not compared to each other in terms of learning gain. Of the 24 participants, 12 completed the VR-based learning tutorials, while 12 with the desktop-based tutorials. We also balanced relevant maths literacy within each group—among the 12 participants in each of the two groups, 6 were mathematically ‘literate’, while the other 6 were ‘novices’. A participant was deemed mathematically literate for the purpose of this study if they reported having received formal education in *complex numbers*.

After expressing interest in partaking in the study, suitable candidates were contacted by email with step-by-step instructions on how to participate. Participants were also sent a digital consent form (PDF) to read, sign and send back to the researcher. A link to a Zoom meeting on an agreed upon time was then sent to the participant.

After participants joined the Zoom meeting, we sent them a link to the pre-test, to fill out on their own computer. Upon completion of the test, they were provided with a link to some primer material designed to introduce them to basic QC notation, and asked to read it. Then, learning tutorial A was remotely activated. Participants were asked to first complete tutorial A, either in their web

browser or using their VR headset (depending on the experimental condition). Once completed, they were given an opportunity to take a break. When they were ready again, tutorial B was remotely activated, and they were similarly asked to complete it.

After completion of the learning tutorials, participants were sent the post-test to fill out. They were also given the shorter 8-question variant of the ‘User Experience Questionnaire’ (UEQ-S) to reflect on the learning tutorials in terms of pragmatic and hedonic quality. The short variant UEQ was used since the learning tests themselves were already quite lengthy [41]. Finally, we conducted a brief informal interview to gain qualitative insights into their experience, including their prior conceptions of QC (if any), what they found difficult, how they recalled information during the post-test, and what they thought could be improved. Upon completion of the experiment they were provided with a \$10 gift card.

In summary, our study tested for the effects of two independent variables—MEDIUM (between-participants, with two levels, *VR* and *Desktop*), and experience with relevant mathematics (i.e. complex number), MATHS (between-participants, with two levels, *Novice* and *Literate*)—on one dependent variable—the LEARNING GAIN, measured as the normalised difference between the scores in the pre- and post-tests.

3.3 Data Processing

We collected data from 24 participants, with each participant completing 2 knowledge tests per tutorial, each comprising of 5 questions and 5 respective confidence scores (10 responses per test). Both tests were also administered 2 times per participant, before and after exposure to the learning systems. Therefore, in total there were $24 \times 2 \times 10 \times 2 = 960$ data points collected measuring learning outcomes. Additionally, each participant answered the UEQ-S, leading to a further $24 \times 8 = 192$ data points measuring their experiences with the learning tutorials in terms of pragmatic and hedonic quality.

For each knowledge test completed, a ‘normalised score’ was computed in the range $[0, 1]$. As discussed earlier, it was important to take into account the confidence associated with a given test answer. Therefore, for each question, confidence in terms of the raw 7 point scale was mapped to the range $[0, 1]$, where 0 represents ‘no confidence’ and 1 represents ‘complete confidence’. This was multiplied with the score for that question, which would be either 0 or 1 depending on if it was correct or incorrect. The result was a ‘normalised question score’, also in the range $[0, 1]$. Finally, the normalised test score could be computed by averaging the normalised question scores.

We were not interested in the individual test scores per se, but the *change* in scores between the pre-test and post-test, because the aim was to measure if the tutorials themselves resulted in any learning. Therefore, for each participant, and each learning test, a LEARNING GAIN was calculated simply by subtracting the normalised pre-test score from the normalised post-test score. This would serve as the dependent variable in the subsequent statistical analysis. Note that ‘negative learning’ could theoretically occur under this model if the post-test score was lower than the pre-test score, e.g. LEARNING GAINS were in the range of $[-1, 1]$.

	Tutorial A		Tutorial B	
	Mean	Std Dev	Mean	Std Dev
Desktop				
Maths Novice	0.06	0.10	0.12	0.15
Maths Literate	0.23	0.21	0.37	0.25
VR				
Maths Novice	0.14	0.21	0.21	0.29
Maths Literate	0.66	0.14	0.49	0.36

Table 1: Means and standard deviations of the LEARNING GAINS for tutorial A and B, grouped by MEDIUM and MATHS.

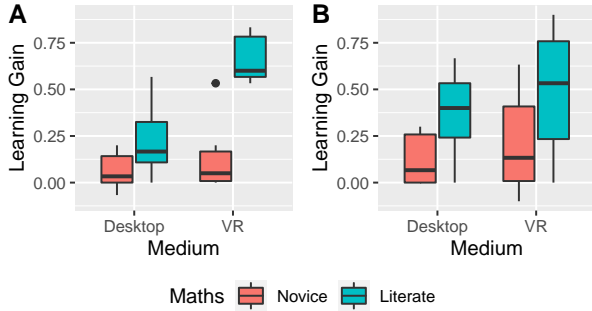


Figure 6: Plots showing the mean LEARNING GAIN for tutorials A and B, grouped by MEDIUM and MATHS.

4 RESULTS

Table 1 summarises the LEARNING GAINS for both tutorials, broken down by condition (MEDIUM and MATHS). In terms of MEDIUM, the mean LEARNING GAIN was greater for participants in the VR condition over the Desktop condition in all cases where MATHS is kept constant. Likewise, in terms of MATHS, the mean LEARNING GAIN was greater for participants in the Literate condition over the Novice condition in all cases where MEDIUM is kept constant.

4.1 Learning Gains

For the learning gains associated with tutorial A, the data was found to be not-normally distributed. Therefore, the data underwent an Aligned Rank Transform (ART) before further analysis [51]. A two-way ANOVA indicated that both MEDIUM ($F_{1,20} = 18.28, p < 0.01$) and MATHS ($F_{1,20} = 27.43, p < 0.01$) had a significant main effect on LEARNING GAIN. There was also a significant interaction effect present ($F_{1,20} = 6.90, p = 0.02$, Figure 6A).

Regarding tutorial B, a two-way ANOVA indicated that only MATHS ($F_{1,20} = 5.71, p = 0.03$), not MEDIUM ($F_{1,20} = 0.87, p = 0.36$), had a significant main effect on LEARNING GAIN. There was no significant interaction effect present ($F_{1,20} = 0.02, p = 0.90$). These results are summarised in Figure 6B.

Figure 7 shows the LEARNING GAIN for each individual participant. There is notable variability in the performance between some participants within their respective experimental conditions (e.g. P19 vs P21). Furthermore, learning in tutorial A did not always coincide with learning in tutorial B (e.g. P20, P22).

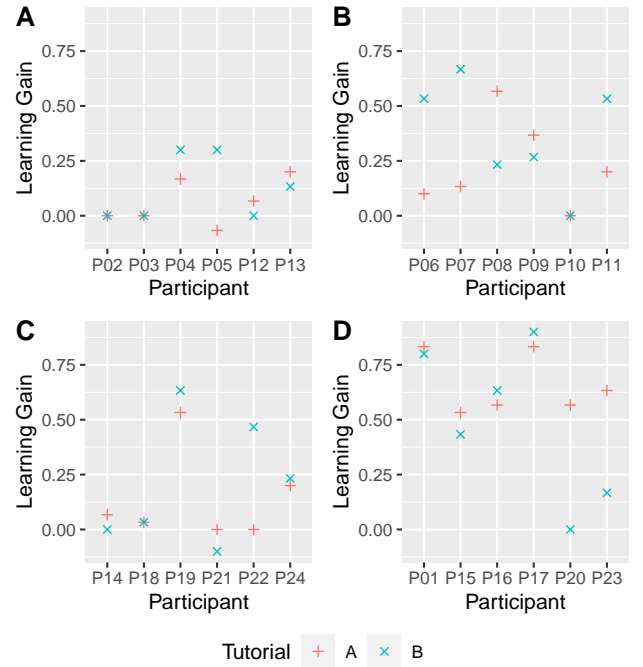


Figure 7: Plots showing per-participant LEARNING GAIN for each tutorial. Participants are grouped by (A) Desktop/Novice, (B) Desktop/Literate, (C) VR/Novice and (D) VR/Literate.

4.2 UEQ-S Scores

Table 2 shows the mean UEQ-S scores grouped by MEDIUM and MATHS. Ratings according to recent benchmarks [14] are also shown. The tutorials were well received ('excellent') by Literate participants in terms of hedonic quality, regardless of the medium of interaction. VR/Novice participants also rated the tutorials favourably in this regard ('above average'). In terms of pragmatic quality, only VR/Literate participants rated the tutorials favourably ('good'). Overall, VR/Literate participants rated the tutorials most favourably ('excellent'), followed by Desktop/Literate participants ('good'), then VR/Novice participants ('above average'), and finally Desktop/Novice participants ('bad').

	Pragmatic	Hedonic	Overall
Desktop			
Maths Novice	0.62 (bad)	0.71 (<avg.)	0.67 (bad)
Maths Literate	1.04 (<avg.)	2.04 (exc.)	1.54 (good)
VR			
Maths Novice	0.96 (<avg.)	1.21 (>avg.)	1.08 (>avg.)
Maths Literate	1.67 (good)	1.79 (exc.)	1.73 (exc.)

Table 2: UEQ-S scores showing hedonic, pragmatic and overall scores of the learning tutorials, grouped by MEDIUM and MATHS ('exc.' means excellent, while '<avg.' and '>avg.' means below and above average respectively).

4.3 Qualitative Results

Two participants in the VR condition were positive in terms of how the Bloch sphere visualisation (tutorial A) supported information recall. One participant (P20) mentioned *“I’m a visual guy...I remember quite vividly when I rotated the lever to the various states”* in terms of answering post-test questions. Another participant (P15) similarly stated that it was *“easy to imagine the qubit in a certain state”* during the post-test, and that they *“remembered the action of moving the lever”*. Two participants in the VR condition expressed a desire for *sound* to have been utilised. One participant (P01) stated that it would have been good to *“use audio for text”*, while another VR participant (P23) similarly stated *“I would appreciate having a voice-over as audio support”*. The same participant took this suggestion one step further by expressing the desire to be able to use *“voice commands”* to progress through the tutorials.

Desktop participants were sometimes critical about the means of interaction in the tutorials. For example, a participant (P02) likened the overall experience to a video game, noting that *“it’s hard to manipulate objects in a video game environment”* and they needed *“more time to associate keys with movements”*. The same participant also stated that *“it was hard to get an angle on the [Bloch] sphere to see it from all angles”* (the W-S-A-D keys and mouse allowed for ‘conventional’ first-person navigation). Another participant (P05) stated that the *“mouse was overly sensitive”*, while yet another (P07) mentioned that they wished they could *“move the [Bloch sphere] lever quicker”*.

Some participants (typically maths novices) expressed difficulty in terms of understanding mathematical concepts and terminology. One participant (P21) stated that they *“found the formulas difficult”* and that the tutorials were *“very heavy on the maths...more advanced physics level”*. Another participant (P24) noted that *“rotations around axes were confusing”*. Additionally, a couple of participants (P02, P12) complained about having difficulty understanding the *“Greek letters”* in the tutorials.

5 DISCUSSION

5.1 VR as a Tool for Learning QC

Our results indicate that VR was a more effective learning medium for tutorial A when compared to the desktop application. This provides evidence that the Bloch sphere visualisation is particularly well-suited to a VR environment. One way to explain these results is through the lens of *embodied cognition* – the idea that our sensorimotor system plays an intrinsic role in how we think and learn [49]. An isomorphic mapping between a VR environment and the real world allows us to enact our sensorimotor system in order to facilitate this process. The means of interaction with the VR Bloch sphere lever is a prime example of this. Grabbing and rotating an object in a 3D world is a natural human movement which requires minimal learning when applied in a novel context. In a 3D virtual world, we require a way of manipulating the objects within it, since they are not physically present in the real world. While it is possible to facilitate this via a keyboard, mouse or touch-screen, this requires that the brain ‘translates’ between an imagined spatial action and the relevant inputs (e.g. key presses). This in itself is a process that, at least initially, has to be *learned*.

Previous work has described the inefficiency of this process in the context of computer-aided design (CAD) software [3]. Using a 2D computer interface to map between the 3D real world and a 3D virtual world inevitably requires some ‘compression’ of information in-between. In an immersive VR environment this compression does not necessarily have to take place. Qualitative feedback affirmed the notion that the means of interaction in a typical desktop simulation can pose a barrier between the user and the virtual environment. Desktop participants expressed difficulty performing rotations and observing the sphere from different angles via a keyboard and mouse. Of course, it is important to consider the possibility that a different control scheme might have yielded a ‘better’ interactive experience in the desktop condition. However, there will always be an element of subjectivity with respect to the ‘best’ controls, and control sensitivity, for a standard computer simulation. This is not nearly as apparent in an immersive VR context where interaction can be facilitated via a natural movement like grabbing.

The Bloch sphere visualisation may also benefit from stereoscopic vision, which is unique to VR as a medium over a standard desktop display. Stereoscopic vision improves perception of relative depth [37]. It is known that stereoscopic vision is particularly useful for conducting manual tasks which are visually guided, such as threading a needle [37]. It is not a stretch to compare such tasks to rotating the Bloch sphere lever, especially when trying to rotate the lever in a precise way. Within educational contexts, a recent study investigating the learning of human anatomy found that 3D models were superior to 2D projections, and that stereoscopic vision was the main driver of improved learning [47]. Similar findings on the benefits of stereoscopic vision in education have also been described in a virtual environment context [29].

In the multi-qubit context there was greater learning in the VR condition compared with the desktop condition, however, this was not statistically significant. Therefore, it is not clear if VR can confer a distinct pedagogical advantage in multi-qubit contexts. The less pronounced difference between mediums here can most likely be explained by the more primitive interactions in tutorial B. Quantum measurement only involved touch interactions, in contrast to the three-dimensional rotations required when manipulating the Bloch sphere. In other words, greater immersion and haptics *alone* were not sufficient to significantly improve learning. From a technological perspective, haptics in VR is relatively primitive compared with visuals at this point in time [9]. In tutorial B, it was simply controller vibration which offered a basic haptic effect when performing a quantum measurement. A more advanced haptic system might allow for a more convincing and memorable experience, leading to better recall. Previous work has shown that haptics can be a powerful learning tool in different contexts, especially when also coupled with more advanced technologies [34].

5.2 Impact of Prior Knowledge

Unsurprisingly, in both tutorials, mathematically literate participants notably outperformed novices. This is not surprising given the use of mathematical concepts in both tutorials. However, while maths literacy predicted greater learning in both cases, this was significantly more pronounced in the VR condition in tutorial A. As already discussed, those in the desktop condition had to contend

with a less natural means of interaction. In addition, it is clear that those who were maths novices faced a larger challenge from the onset. Not only did they not have a grounding in relevant constructs such as complex numbers, but mathematical language was generally overwhelming for them (qualitative feedback indicated issues comprehending the “Greek letters” for instance). A maths literate individual would have a framework of understanding in place to comprehend mathematical notation. Therefore, their working memory could be dedicated to more important features of the Bloch sphere representation.

UEQ-S scores also supported this notion. On pragmatic quality, only VR/literate participants rated the tutorials favourably (‘good’). It is likely participants in the other conditions struggled either due to difficulties with interaction or mathematics. It should be noted that on hedonic quality VR/novice participants still rated the tutorials favourably (‘above average’). This suggests that VR might be an exciting way for lay-people to engage with difficult ideas, even if learning itself is minimal.

In some cases there was significant inter-individual differences in terms of learning, even within a given experimental condition. While it is likely that this variation was introduced by differences in prior knowledge, it is also possible that individuals employed different learning strategies throughout the tutorials. Previous work has shown that there can be significant inter-individual differences in approaches to sensorimotor learning tasks [6] as well as levels of engagement during VR studies [52].

5.3 VR for Education

In practice, it is feasible that the same VR Bloch sphere developed for this research could be deployed for use by students as part of a university level QC course. An important premise of our work is that it investigates VR as a complementary *tool*, rather than a replacement for traditional education. A first-principles approach should play an important role in QC education, and regardless of the learning mediums employed, there is intrinsic complexity associated with QC as a discipline. It is important not to set unrealistic expectations about what a different medium alone can achieve. In a practical setting, such as a university course, one might imagine immersive VR simulations helping students develop conceptual understanding and consolidate existing knowledge garnered via lectures and workshops. The end goal of this research is not just to explore the veracity of this notion for academic purposes, but also help educators to integrate creative means of teaching into existing curricula.

Our work provides further evidence that VR can be an effective tool in education more generally. This aligns with previous work investigating the use of VR in various educational contexts [36]. Educational scenarios which rely on enhanced depth perception as well as non-trivial interaction with an environment may be particularly well-suited to VR. In these scenarios, simply being able to easily view an object from different angles can enhance learning. Garcia-Bonete et al. [11] made similar propositions after investigating VR (and AR) in a structural biology learning environment. The authors suggest that VR technologies allow students to easily observe complex structures (e.g. protein molecules) from different directions. They note that increased depth perception also allows

students to more easily appreciate the structure of such an object. On a more macroscopic scale, it has similarly been shown that immersive virtual environments facilitate easier comprehension of complex three-dimensional structures such as cave systems [42]. These notions are in line with our findings, particularly with respect to the Bloch sphere visualisation.

5.4 Limitations

There are several limitations in the present work. First, while there is evidence that the Bloch sphere visualisation is better suited to VR over a standard computer based simulation, this may not be the case for other representations of ‘single-qubit systems’. The Bloch sphere is just one way of representing a single-qubit system, and it may be the case that other visualisations can convey the same underlying theory in a more effective way within non-VR environments (conversely, in a multi-qubit context, a different approach to learning might be better suited to a VR environment). Additionally, the Bloch sphere is conceptually focused on the principle of superposition, rather than other concepts such as quantum measurement. Nonetheless, given the Bloch sphere’s well-established role in QC education, the results from this experiment present a significant finding. Second, although multiple-choice question (MCQ) tests are a minimally resource intensive and reliable way to measure learning, they can sometimes overestimate learning [10]. We mitigate this issue by including measures of confidence in the tests in order to scale scores accordingly (‘normalised scores’). Regardless, this still relied on an accurate and honest self-assessment of knowledge, and it was possible that some score improvements reflected inaccurate confidence increases rather than true learning.

Finally, VR participants had to own or have access to an Oculus Quest HMD, as a result of COVID-19 limiting in-person data collection. Thus, differences in participant’s setup were inevitable. However, we did take the necessary steps to ensure that our software would run well and similarly on all participants’ machines.

6 CONCLUSION AND FUTURE WORK

Our work aimed to explore how immersive VR could be utilised as an educational tool for quantum computing. An evaluation of two learning tutorials exploring single-qubit and multi-qubit concepts revealed that the ‘Bloch sphere’ visualisation was well-suited to VR as a medium over a desktop environment. Furthermore, mathematics literacy was an important factor in facilitating greater learning overall, but this was notably more pronounced when VR was the medium. VR did not significantly improve learning in the multi-qubit context over the desktop-based equivalent.

Future work may benefit from extending upon the VR Bloch sphere visualisation. While the surface of the Bloch sphere elegantly captures the state space of a pure single qubit state, the points *inside* the sphere are also physically relevant, and represent what are called *mixed* states. Mixed states can be challenging for beginners to conceptualise since they may be confused with superposition states. It may also be interesting to utilise the Bloch sphere visualisation in extended-reality (XR) contexts – VR may not be the only medium where it can excel as a visualisation. In a mixed-reality environment, it may be possible to visualise the Bloch sphere along-side existing desktop environments used in education, such as the QUI [28].

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